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Assessing sub-regional water scarcity using the groundwater footprint

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ABSTRACT

The groundwater footprint (*GF*) is an innovative concept that is used to evaluate groundwater sustainability, and it can be defined as the area required to sustain groundwater use and groundwater-dependent ecosystem services in a region. In this study, we evaluated water scarcity on a sub-regional scale using a water stress indicator defined as the ratio of groundwater footprint to aquifer area *GF/A* that indicates the sustainability of the aquifers. The higher the stress indicator is, the less sustainable the aquifer is. This study was conducted in the northern part of Colombia; it involves 19 municipalities located in the Sucre department and six main aquifers. Through the use of 5000 interviews, the study calculates water abstractions in the study area, such as cattle, commerce, industry, homes, agro-industry and agriculture; however, only domestic demand associated with groundwater fed aqueducts and groundwater wells was considered because it represents almost 80% of the total abstractions. In addition, the study considered climate change and population growth and how they may affect the *GF*. The analysis shows that the water stress indicator for the Morroa aquifer has the highest groundwater stress among the six aquifers subject to investigation. GF is considerably higher than many of the world aquifers. Using the same indicator, we compared different mitigation alternatives to increase the sustainability of the Morroa aquifer. Results show that a combination of artificial recharge measures with an alternative source able to supply at least 50% of the domestic consumption appears to be the best choice to make the aquifer more sustainable. *GF* is a simplified yet robust way to support decision-makers and stakeholders so as they can evaluate water management policies and strategies.

1. Introduction

In the last few years, the demand for groundwater has increased considerably to be able to supply the needs of economic sectors and domestic use. At world level and in proportions that vary widely from one country to the next, especially in those regions where there is no surface water and groundwater is the only source, groundwater exploitation covers approximately: 40% for industrial activities; 20% for irrigation and 40% for drinking water needs (Zektser and Lorne, 2004). The high demand of this resource and the lack of proper management strategies have generated some concerns around a possible scarcity of groundwater in certain regions due to an accelerated decrease in water levels (Zektser and Lorne, 2004; Wada et al., 2010; Rodell et al., 2009; Konikow and Kendy, 2005).

A novel indicator used to study sustainability, vulnerability and stress of aquifers is the groundwater footprint concept- GF (Gleeson and Wada, 2013). The GF determines the volume of water that is required for a consumer or producer, also known as blue water (Aldaya et al., 2012), without taking into account the surface water. It is used to estimate groundwater stress and was introduced for the first time by Gleeson et al. (2012). Groundwater stress is an indicator of water scarcity, calculated as the ratio of the groundwater footprint and aquifer area. The aforementioned indicator focuses on groundwater quantity and ignores the resourcés possible contamination problems, which may result in a smaller water footprint and stress.

There are well-documented studies of the largest global aquifers' water footprint and scarcity (e.g. Gleeson and Wada, 2013; Gleeson et al., 2012; Hoekstra et al., 2012) that help to classify those regions with an elevated water stress, either by the characteristics of the environment or the overexploitation of the resource. Colombia has a low groundwater footprint in the majority of its territory (Hoekstra et al., 2012); however, on a sub-regional or local-level, the situation may be different but there is not enough evidence in the literature.

This is the case of the aquifer system that is located in the Sucre

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department, found in the north of the country, where small creeks represent the main water surface bodies but run dry several months of the year; hence, major source of supply is groundwater. Besides, the groundwater abstractions in the region, which are mostly for domestic use, are not fully controlled by the environmental entities, as the exploitation areas are very large. Every year the National Water Study shows the condition and dynamics of the water in Colombia (VYDT, 2014); however, the study does not establish a clear division between surface and groundwater footprint. Moreover, the analysis undertaken of hydrogeological zones is more on a national than a sub-regional or local scale. For this reason, it is necessary to assess the current conditions of the aquifers and establish if the levels of water use could lead to water shortages and ecological damage in the short and long term. We believe that the groundwater footprint and groundwater stress indicators, calculated in a spatial way, will provide a more reliable and accurate overview of the situation in Sucre and will be a useful tool for the decision makers to implement suitable water management strategies. In this respect, the main goal of the research is to investigate the applicability of the groundwater footprint concept in a sub-regional level to define water scarcity and design measures to improve sustainability.

2. Characteristics of the study area

The study area is located in the Sucre department in the north of Colombia, which is a part of the Caribbean region. This department hydrography is composed by a perennial natural network of rivers and marshes located in the southern part (Fig. 1).

Conversely, in the northern part rivers run dry most of the year. The six main aquifers of the Sucre department located within 19 of the 26 municipalities that conform the department represent an area of 5000 km^2 approximately (Fig. 2a). This area has an alternate wet and

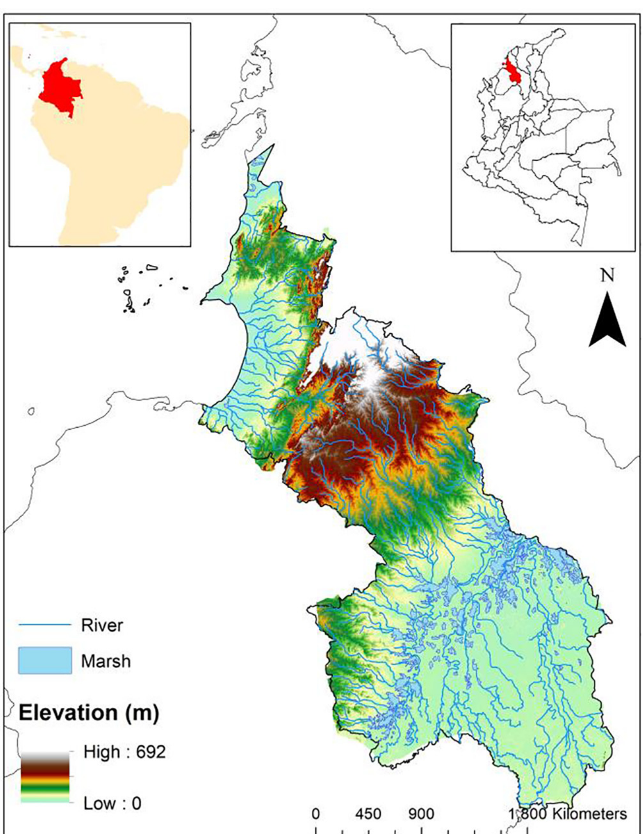

Fig. 1. Sucre Department: River Network and Digital Elevation Model (DEM).

dry season, the driest months being from December to March and the rainiest from May to October. April and November are transition months, however most part of the year, specifically during the dry season and the transition months, the surface water streams disappear due to the high temperatures reaching 34 °C and an average temperature of 28 °C.

Additionally, in most of the region, the climate may be classified as tropical savanna, with a moderate to high precipitation between 1000 and 1800 mm and a high evapotranspiration (1400–1600 mm), estimated by the Institute of Meteorological, Hydrological and Environmental Studies (IDEAM) with an evaporation tank and empiric equations. Agricultural and livestock activities that take place in the zone supply their necessities mainly through rainwater reservoirs. In this sense, for the other activities, other sources of water such as groundwater are necessary to ensure a continuous supply of water. Therefore, for domestic use and drinking water, the community uses mainly aqueduct systems supplied by groundwater.

Sucre has outcrop sedimentary rocks and unconsolidated sediments with a marine, transitional and continental origin, the ages of the formations range from the upper cretaceous to quaternary epochs. The study focuses on six aquifers identified in Sucre (Colombia). Fig. 2b presents the main aquifers within the study area and Table 1 the corresponding area and municipalities within each of them.

The Morroa aquifer is the biggest of the six aquifers that comprise the system with an area of around 1000 Km^2 (Pérez-García et al., 2009, 2014). It supplies a population that is close to 400,000 inhabitants (National Administrative Department of Statistics-DANE, 2015) located in the municipalities of Corozal, Ovejas, Los Palmitos, Morroa, Sincelejo and Sampués (Corporacion Autonoma Regional de Sucre, 2005). Only Corozal, Morroa, Sincelejo and Sampués have a central aqueduct (Salazar et al., 2011). Main streams within the study area are the *Arroyo Grande de Corozal* and the *Arroyo Morroa*; both run over the Morroa aquifer recharge area, but only the Arroyo Grande de Corozal remains during the dry season as it is mainly fed by return water from Sincelejo urban center.

The Morrosquillo aquifer is located in the southern Colombian Caribbean basin and supplies a population that has close to 100,000 inhabitants from the municipalities of San Onofre, Santiago de Tolú and Coveñas (National Administrative Department of Statistics (DANE), 2015). The first two municipalities have a central aqueduct while in the other municipality water is supplied mainly from artisanal extraction wells and rainwater collectors (Wada et al., 2010). The resource is supplied by around 800 wells (Corporacion Autonoma Regional de Sucre, 2005), of which less than 1% have been legalized (Corporacion Autonoma Regional de Sucre, 2005) and, on average, 80% is utilized for human supply (Corporacion Autonoma Regional de Sucre, 2005).

Other aquifers have been reported in the literature associated with the study area. In particular, the Betulia, Toluviejo, San Cayetano and El Roble aquifers have been identified as groundwater bodies in a study carried out by the Regional Environmental Authority (Corporacion Autonoma Regional de Sucre, 2005); however, there is scarce available information on these formations in the literature.

The Betulia aquifer is thought to supply water to a population of close to 92,000 inhabitants (National Administrative Department of Statistics (DANE), 2015) from the municipalities of Buenavista, Galeras, San Juan de Betulia, San Pedro and Since. Toluviejo and San Cayetano appear to supply around 82,000 inhabitants living in the municipalities of Palmito, Toluviejo and San Onofre while El Roble appears to supply the municipality of El Roble (10,000 inhabitants).

The purpose of this study is to evaluate water scarcity on a sub-regional scale using a water stress indicator that is based on the concept of a groundwater footprint. Additionally, we aim to assess the suitability of this indicator in the design of policies and water management strategies in order to ensure the sustainability of the water supply and reduce the pressure of local aquifer systems. The study focuses on six aquifers identified in Sucre (Colombia).

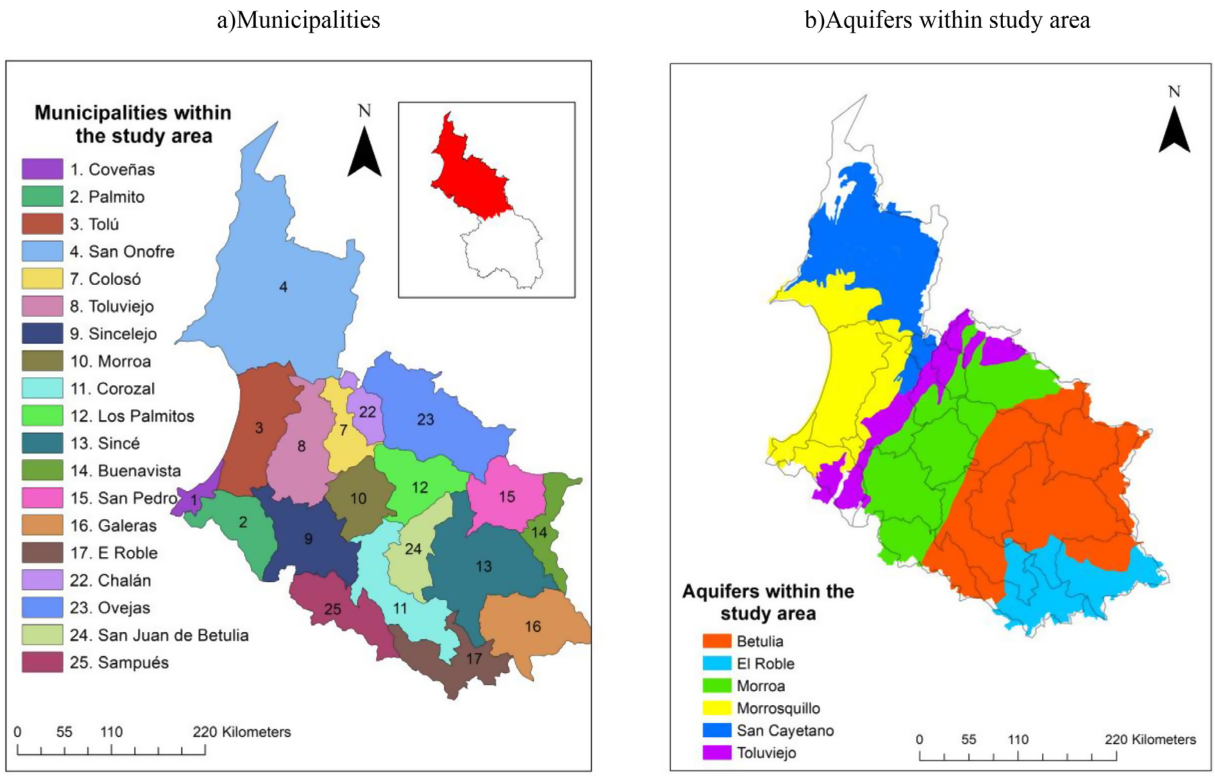

Fig. 2. Municipalities (a) and aquifers (b) within the study area.

Table 1
Main aquifers area and municipalities.

Aquifer	Area (km^2)	Municipalities
Betulia	1557	Betulia, Buenavista, Galeras, San Pedro, Sincè
Morroa	1000	Colosó, Corozal, Morroa, Ovejas, Sampués, Sincelejo, Los Palmitos, Chalán
Morrosquillo	793	Coveñas, Tolú, San Onofre
Toluviejo	384	San Onofre, Toluviejo, Palmito
El Roble	477	El Roble
San Cayetano	743	San Onofre, Toluviejo, Palmito

3. Methodology

Water scarcity in a region is defined based on Aldaya et al. (2012) as the ratio of the blue water footprint to the blue water available. In a region in which only groundwater provides water for the different types of demand, the definition needs to take into consideration the ratio of groundwater footprint to groundwater availability. The groundwater footprint (*GF*) can be defined as the area required to sustain groundwater use and groundwater-dependent ecosystem services[1] in a region of interest, such as an aquifer, watershed, municipality or community. In more formal terms, *GF* can be defined as (Gleeson et al., 2012):

$$GF = A[C/(R-E)] \quad (1)$$

where C is the area-averaged annual abstraction of groundwater, R is the recharge rate and E is the groundwater contribution to environmental streamflow. All the units of these three parameters are expressed in m/day. A is the areal extent of any region of interest given in m^2. If there is an absence of perennial surface water bodies, we could neglect the groundwater contribution to streamflow. Then, Eq. (1) would become:

$$GF = A[C/R] \quad (2)$$

Groundwater footprint is a water balance between aquifer inflows (R) and outflows (C). The ratio of groundwater footprint to aquifer area GF/A has been used as an indicator of groundwater stress: $GF/A > 1$ indicates unsustainable groundwater consumption that could affect groundwater availability, and $GF/A \gg 1$ indicates unsustainable groundwater mining, often groundwater recharged under past climatic conditions. A ratio $GF/A < 1$ represents sustainable groundwater extraction.

Estimation of groundwater footprint on a sub-regional level is a challenge as actual groundwater abstraction is often poorly known and recharge requires catchment-scale hydrological modeling. In global and national scale studies (e.g. Gleeson et al., 2012) these parameters have been derived and downscaled from global models, and groundwater consumption values have been reported by countries. Using this methodology, the literature has reported important findings. In particular, Gleeson et al. (2012) confirmed that well-documented depleted groundwater aquifers, such as the Upper-Ganges, North China and Central Valley have large groundwater footprints, but they also presented evidence of groundwater overexploitation in not that well-documented aquifers such as the Persian, Arabian, South Caspian and Western Mexico Aquifers. GF/A ratio for these aquifers ranges between 20 and 100. They also estimated that the averaged global ratio GF/A is around 3.5 when considering environmental flows and 2.0 when E is set to 0. Within this global analysis, aquifers located in Colombia were reported to have a GF/A smaller than 1.

A semi-distributed hydrological approximation is proposed to be able to estimate the recharge rate that takes into account soil texture, land-use and slopes in order to delineate hydrological response units (HRU) (Flügel, 1995). For each HRU, we performed a water balance using the expression described by Scanlon et al. (2002), which can be expressed as:

[1] Groundwater – dependent – ecosystem: ecosystem services provided by groundwater such as wetland, aquatic stream-bed, coastal lagoon and terrestrial ecosystems.

$$P-ET = R-Q_s + \Delta S \quad (3)$$

Where every parameter of the equation is in length units [L]. To estimate the precipitation (P) and evapotranspiration (ET) values, climatological data from stations located within the study area is used. The partition between runoffs in (Q_s), infiltration (R) and the change between surface and sub-surface storage (ΔS) for each HRU is calculated based on the concept of approximated infiltration capacity (Q_{cap}), presented by Pérez et al. (2011). Since the conditions for Hortonian runoff (named after Robert Horton occurs when the water-input rate exceeds the infiltration capacity of the surface soil for a period long enough to generate ponding in excess of depression storage- Pérez García, 2011) are given when the rainfall intensity exceeds the infiltration capacity of the soil, it is expected that the approximate infiltration capacity Q_{cap} is indicative for whether or not a certain rainfall event will generate Hortonian runoff at a particular HRU. Q_{cap} is in units of L/T and can be calculated as:

$$Q_{capi} = K_{rwi}\, k_{si} \quad (4)$$

where K_{rw} is the relative permeability of the medium $[-]$, and k_s is the saturated hydraulic conductivity [m/day]. This study utilized the values presented by Carsel and Parrish (1988) to define the average and standard deviation of K_{rw} and k_s.

In order to estimate the recharge, we compare Q_{cap} with Q_r, which is the total water input rate (rainfall rate in this case); this can be defined as the difference between precipitation and evapotranspiration ($P-ET$), and it establishes that:

$$\begin{aligned} &\text{If } Q_{cap} > Q_r,\ \text{ then R is set to } Q_r \text{ and } Q_s-\Delta S = 0 \\ &\text{If } Q_{cap} < Q_r,\ \text{ then R is set to } Q_{cap} \text{ and } Q_s-\Delta S = Q_r-Q_{cap} \end{aligned} \quad (5)$$

4. Results and discussion

4.1. Abstractions

The calculation of the abstractions can be made using information on consumption from water concessions typically provided by environmental entities or water supply companies. However, this was not possible for this case as most of the municipalities within the study area lack of information about consumption. The latter is because in this municipalities there are local water infrastructure rather than municipal water distribution networks. For the particular case of Sincelejo (capital city of the Sucre department) use of information is restricted as a private company operates it.

To overcome this problem, we performed an extensive survey in twelve municipalities in which the majority of the population has no access to aqueduct and predominate rural areas. Through georeferenced door-to-door interviews, we estimated the water consumption for domestic uses, industrial activities, livestock, irrigation, the commercial sector and institutional centers. The interviews included questions regarding quantity of water used for different activities, the number of inhabitants in a house, products made in the industries, number of animals in a farm and sources of water supply. In particular, people was asked for water consumptions of each of their daily activities measured in a language they can understand (recipients they use to collect water) as it can be observed in the interview text (Appendix 1). The recipient volumes are translated into liters and the house/business unit water consumption are estimated. More than 5000 interviews were given and processed by a local-team over a period of seven months.

A statistical analysis was then performed that included goodness-of-fit tests such as the Chi-squared test. Table 2 presents a summary of the technical details of the survey. The analysis allows evaluate consistency of the data.

Surveys conducted in the study area helped to establish the volume of groundwater extracted annually and the main activities that demand the resource. We can state that the number of groundwater withdrawals

Table 2
Technical details of the door-to-door survey.

Parameter	Values
Total number of interviews	5160
Pearson Chi-squared	324,74
Likelihood function	245,14
Number of valid interviews	5096

(groundwater fed aqueducts and wells) used to supply domestic and drinking water necessities are high (78.5%) There is a lower use for the commercial/institutional sector (8.1%), agro-industrial activities (5.6%) and cattle (6.1%); values associated with the industrial and agricultural sectors are negligible (1.2% and 0.4% respectively). The commercial/institutional sector is mainly supplied by the aqueduct system; this sector is made up by schools, universities, health centers and hotels, which are mostly located in Sincelejo. Cheese production and its derivatives are the most popular activities undertaken by the agroindustrial sector, but this is only a small-scale activity, and in many cases rainwater is used for the production processes. Livestock and agriculture are important economic sectors for the department; however, in most cases they supply their needs using rainwater. Finally, the only a few municipalities have an industrial sector, such as Sincelejo (which is the capital city of Sucre), are supplied by aqueducts. Based in this context, the water consumption analysis will focus on the domestic activities that use well direct extractions or through aqueduct systems.

From the abovementioned survey, we also estimated average, minimum and maximum water demand per capita to supply basic needs (domestic use). Table 3 shows the results. From the table, it is possible to infer a similar trend for average and minimum values: average values move between 79 l/d and 96 l/d and minimum values between 11 l/d and 37 l/d. The minimum values reported are below the minimum amount of water required to satisfy a person's basic needs (50 l/d according to the Drinking water and basic sanitation direction, 2000). The maximum values show an important difference in the main cities' pattern of water (Sincelejo, Corozal and Sampués) as well as for the rest of the towns. For the estimation of annual abstraction, we used the average values of daily needs.

Using information from the National Administrative Department of Statistics (DANE, 2015), we estimated the population to 2015 (Table 3). From the Table 3, the municipalities with the highest population are Sincelejo, Corozal, Sampués, Sincé and Tolú. The latter is one of the most touristic places in the department.

To estimate the annual average abstraction (C) in the six aquifers that are subject to investigation, we used the projected population and the groundwater demand. Only domestic demand associated with groundwater fed aqueducts and groundwater wells was considered. Results presented in Fig. 3 show that the Morroa aquifer presents the largest abstractions as it provides water to the greatest number of

Table 3
Inhabitants and Domestic water consumption estimated from the survey and measured in liters per day (l/d).

Municipality	Inhabitants (2015)	Maximum	Medium	Minimum
Colosó	5838	170	79	27
Corozal	62,409	263	97	30
Los Palmitos	19,257	157	83	26
Morroa	14,429	229	92	31
Ovejas	21,091	203	89	11
Sampués	37,925	265	88	19
San Onofre	50,214	253	87	16
San Pedro	16,038	234	92	37
Tolú	33,296	189	85	28
Sincé	33,688	204	98	19
Sincelejo	275,207	293	92	26
Toluviejo	18,897	179	93	28

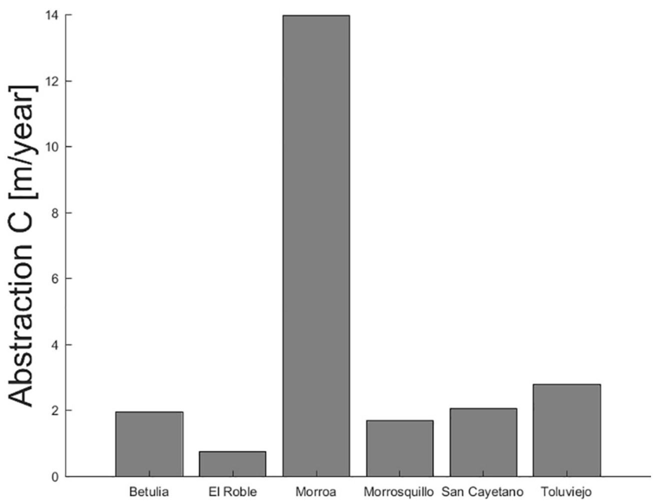

Fig. 3. Annual average abstraction (C) for aquifers within the study area [m/year].

municipalities: seven in total, which include Sincelejo that has around 276,000 inhabitants and Corozal with around 60,000 (projections from National Administrative Department of Statistics (DANE, 2015). As expected, the Roble aquifer is the one that has the lowest abstraction as it only supplies the municipality of El Roble, which has the lowest population. The other four aquifers, Betulia, Morrosquillo, San Cayetano and Toluviejo, have similar abstraction values ranging between 2 and 4 m/yr. This is three to seven (3–7) times lower than the extraction rate for the Morroa aquifer.

4.2. Recharge

To spatially estimate values of recharge rates, we used a semi-distributed hydrological approximation that takes into account soil texture, land-use and slopes to delineate hydrological response units (HRU) (Flügel, 1995). In order to have an updated land-use map (as only a 1985 land-use map from the national authority is available), a supervised classification was performed using *Landsat 8.0* satellite images and a complementary field validation. An updated land-use map was then generated for 2015. Soil texture, an updated land-use map and slope maps are presented as Supplementary material.

A water balance for each HRU was computed using distributed annual rainfall and evapotranspiration according to Eq. (3). Climatological data was available from 19 stations located within the study area. Potential Recharge (R) was estimated using Eqs. (4) and (5). Values obtained for the recharge rate in mm/year are shown in Fig. 4, in which we can see a large variability in terms of recharge in the study area. The potential recharge values go from zero to less than 800 mm/yr. Specifically, higher recharge values are associated with the Morrosquillo, Toluviejo and San Cayetano aquifers. Betulia and El Roble have relatively small recharge rates; Morroa and Morrosquillo have some areas with high recharge values (> 350 mm/yr) but others with much smaller values (< 40 mm/yr).

By integrating recharge values for the aquifers under investigation, groundwater availability (defined as the total recharge of the aquifer) can be estimated. The results in liters/second (l/s) are presented in Fig. 5: maximum is associated with the San Cayetano aquifer (around 70 l/s) and minimum recharge with the El Roble aquifer (less than 5 l/s). Betulia and Morroa have an average recharge that is close to 50 l/s while the Toluviejo aquifer recharge is smaller, with 40 l/s.

4.3. Groundwater footprint and groundwater stress

By using abstractions and recharge rate values, we estimate the

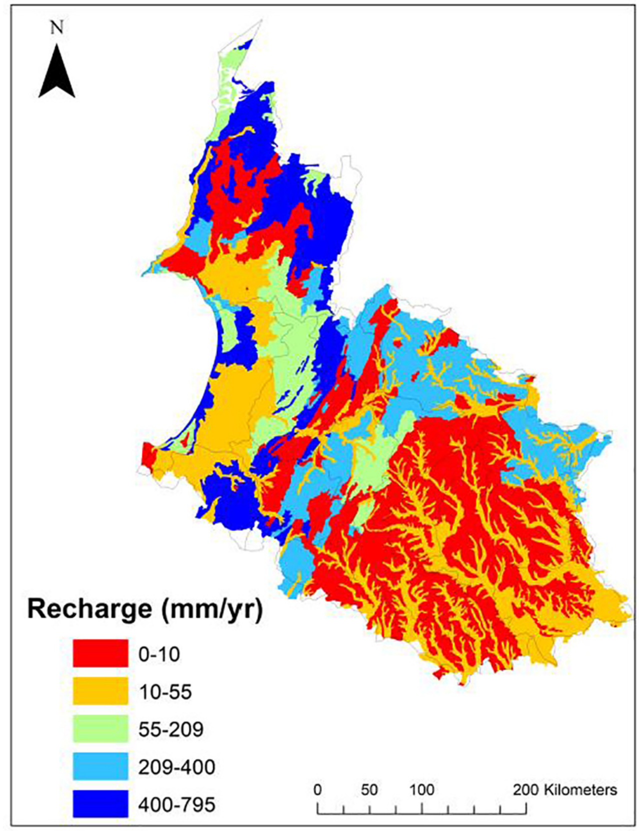

Fig. 4. Distributed recharge rate for the study area (R) [mm/yr].

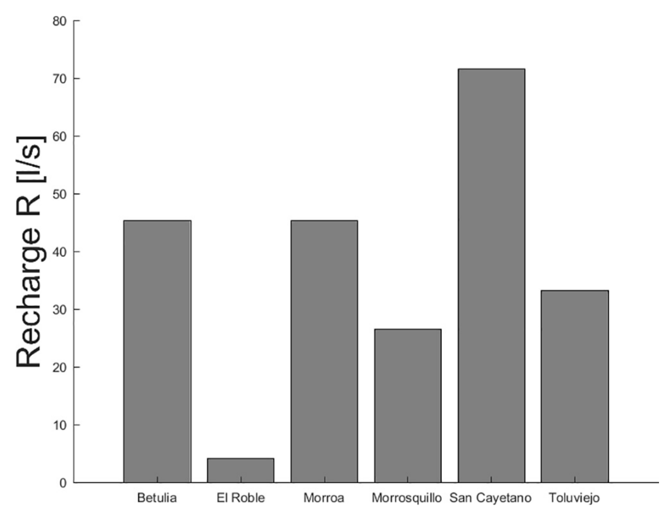

Fig. 5. Groundwater availability [R] for aquifers within the study area [l/s].

groundwater footprint of each aquifer (A schematic representation of the groundwater footprint is included as Supplementary material). From the analysis, the Morroa aquifer appears to have a very high groundwater footprint and high pressure over the resource.

In order to have a better understanding of the aquifer systems' current situations, we estimated the *GF/A* ratio to represent the incidence of water scarcity (i.e. groundwater stress). Aquifers with a high groundwater footprint have unsustainable groundwater withdrawals and groundwater depletion. Fig. 6 presents the groundwater stress ratio (*GF/A*) for the aquifers within the study area. We also give a comparison between the aquifer *GF/A* values with average world values. Also, a comparison between the Morroa aquifer and the most stressed

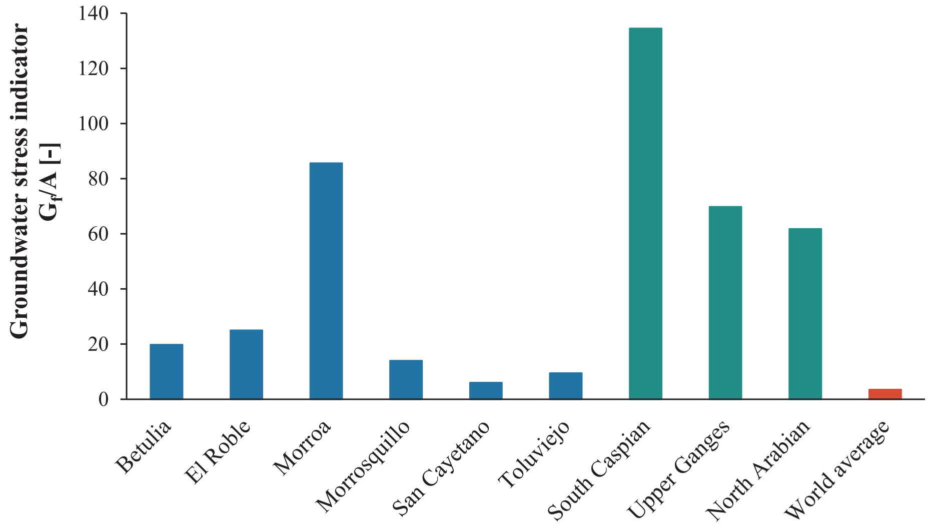

Fig. 6. Groundwater stress (GF/A) of the aquifer system (Blue): comparison with worldwide values (Red) reported in the literature (Gleeson et al. 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

aquifers reported in the literature is presented.

Results show that the six aquifers have GF/A values above 1.0. Morroa, Betulia and El Roble present higher values than the world average; moreover, Morroa has the highest groundwater stress, with a *GF/A* close to 90, which is considerably higher than many aquifers throughout the world. In particular, this value is much higher than the results presented in previous studies in areas with a high population density and high rates of extraction, such as in India (the Upper Ganges aquifer), Saudi Arabia (the North and South Arabian aquifers) and Mexico (the Western Mexico aquifer). It is only comparable to the groundwater stress of the South Caspian aquifer in Iran, which has a *GF/A* around 120 (Gleeson et al., 2012). In contrast, Toluviejo and San Cayetano are the aquifers that have the lowest stress levels, with values of GF/A $<$ 6 (higher than the world average), which means that it is important to pay attention to these regions and avoid the increase of groundwater depletion.

The results of this investigation raise a lot of concerns as the values found indicate that the sustainability of the Morroa aquifer may be at risk.

Groundwater footprint and groundwater stress indicators may offer insights for the design of policies and the implementation of suitable water management strategies. The purpose of these is to ensure the sustainability of the water supply and reduce the pressure that is placed on aquifer systems. In the following section, we evaluate the effect that mitigation strategies may have in terms of reductions for the *GF/A* ratio. We selected the Morroa aquifer to evaluate these strategies because it is in more critical condition and it provides water for more than 500,000 inhabitants; it is the only reliable source of water for half of Sucre.

4.4. Analysis of scenarios

In the context of the Morroa aquifer, some alternatives have previously been discussed some of which have even been tested at experimental sites (e.g. Corporacion Autonoma Regional de Sucre Corporacion Autonoma Regional de Sucre, 2005; Garzón et al., 2002; Bacca et al., 2012). In one case, artificial recharge methods such as recharge pits, recharge wells and infiltration pools have been built and monitored locally. In another, alternative sources of supply such as rivers and lakes located up to 200 km away have been proposed, more specifically, take water from the Magdalena River located 200 km away or from San Benito wetland lakes located 80 km away.

In order to evaluate the potential use of the concept of groundwater stress (*GF/A*) on the process of regional decision-making, five conceptual-level strategies were evaluated. The following strategies are related to artificial recharge measures and alternative sources of supply:

1. Increase recharge by 30% by implementing artificial recharge measures such as pits, wells and infiltration pools. The latter requires the acquisition of land located in the municipalities of Morroa and Sincelejo.
2. Increase recharge by 50% by implementing artificial recharge measures such as pits, wells and infiltration pools. The latter requires the acquisition of land located in the municipalities of Morroa, Sincelejo, Corozal and Los Palmitos.
3. Increase recharge by 50% and replace 30% of the abstraction with an alternative source of supply. The latter requires the acquisition of land located in the municipalities of Morroa, Sincelejo, Corozal and Los Palmitos and the construction of reservoirs and conduction infrastructure.
4. Increase recharge by 50% and replace 50% of the abstraction with an alternative source of supply. The latter requires the same as in the previous point but with much larger reservoirs.
5. Increase recharge by 100% and replace 50% of the abstraction with an alternative source of supply. The latter requires the acquisition of land located in the municipalities of Morroa, Sincelejo, Corozal and Los Palmitos and the construction of recharge wells and infiltration pools along the whole aquifer. This also implies the construction of reservoirs and conduction infrastructure.

To quantify the effect of each alternative on the groundwater sustainability, the groundwater stress ratio *GF/A* was estimated for each one. The results shown in Fig. 7 suggest that for the Morroa aquifer, artificial recharge measures are not enough to improve the sustainability of the groundwater exploitation. In order to make the aquifer much more sustainable, alternative sources of supply may be required. In particular, it appears that 50% of groundwater extraction needs to be replaced by a surface water source. The combination of these alternatives may be the way to reduce risk of water shortage in major towns in Sucre.

In order to evaluate the impact of these strategies, we took into account prospective scenarios that relate to climate change and population growth. Climate change considerations were taken from an official document entitled *Nuevos Escenarios de Cambio Climático para Colombia 2011–2100* (New Climate Scenarios for Colombia 2011–2100), published by the Environmental and Sustainable

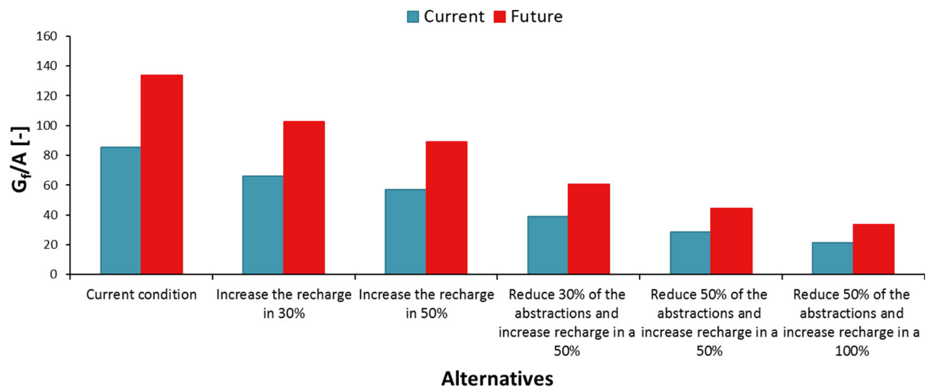

Fig. 7. Analysis of the effect of different alternatives on groundwater sustainability. Current condition - 2015 (Blue), Future condition – 2100 (Red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Development Ministry and the National Water and Climatological Research Institute (IDEAM for its acronym in Spanish), which contains the climate change observations on both a national and State level. The results indicate there will be an 11.3% reduction in precipitation over the next fifteen years; by 2100 the reduction may have increased by up to 16.2%. In terms of temperature, an increase of 2.1° is expected by 2100. (The expected precipitation variation due to climate change that was provided by IDEAM is included as Supplementary material)

To estimate the population growth, official projection data available from the National Administrative Department of Statistics and Data (DANE for its acronym in Spanish) was used (Appendix 2. Shows population data for different years).

Fig. 7 presents an analysis of the strategies based on future scenarios. In this, we can see that there will be a deterioration in terms of sustainability as the groundwater drawdowns will accelerate.

Besides, all these alternatives have an important effect on food and ecosystems services. In this respect, blue water in the region will be affected with a reduction on precipitation, it means a decrease of benefits and services such as food security and energy (Vanham, 2016). As in Fig. 7, there is an increase of the water stress indicator for 2100 for all the alternatives and the current condition. Particularly, for the last, the stress indicator increase almost a 40% in the projected climate scenarios. Food security will be highly affected with a reduction in the access to freshwater, water for industries and water for transportation. Negative impacts on livestock and crops would be also expected. Even in the more optimistic scenario, with the implementation of structural strategies, water stress indicators would remain very high, affecting food security and ecosystems services. From this perspective, reducing the impact of climate change on life quality would imply more comprehensive projects that include further recharge of the aquifers, implementing alternatives sources of supply beyond 50% and strategies to reduce water consumption. The latter, represents a real challenge in a region with temperatures around 35 °C and 30% of the population without access to safe water.

5. Conclusions

We have used the groundwater footprint to assess water scarcity in a savannah climate region located in northern Colombia. To estimate abstractions, we used the results of a door-to-door survey performed in the study area. Domestic, industrial and agricultural consumption were estimated, and the source of water was defined. Recharge was estimated using a semi-distributed hydrological model based on the concept of approximate infiltration capacity.

Our analysis of the study area suggests that current use of some aquifers is unsustainable; this may put economical regional growth at risk and even the future of some cities. In particular, the aquifer (Morroa) that feeds the departmental capital may require effective measures in the short-term that help to reduce the risk of water shortage and push forward agricultural development in the region. According to the results, a combination of artificial recharge with an alternative supply source appears to be the best choice in order to make exploitation of the aquifer more sustainable.

The analysis presented in this study serves as a basis for the design of mitigation alternatives for the Morroa aquifer. Decision-makers and stakeholders may use the results of the model as a starting point to promote further research that allows for an effective set of alternatives to be designed to improve groundwater sustainability. Additionally, the analysis is also useful to be able to incorporate the impact of future climate scenarios and population growth on sustainability considerations.

The results indicate that groundwater footprint is a very useful concept when evaluating groundwater stress and the sustainability of the groundwater exploitation on a sub-regional level. It also appears to be very helpful to evaluate water management policies and strategies. In particular, the *GF/A* ratio proved to be useful to intuitively evaluate the effectiveness of water management measures.

The methodology proposed provides a valuable water management tool to instinctively evaluate groundwater stress on a sub-regional level. It presents a simplified yet robust approach to improve recharge and abstraction estimations, which helps with research into regional aquifers by using an optimal scale of analysis. This tool allows us to move on from the endless discussions on depletion volumes towards the design of suitable solutions and contributes to bridging the gap between hydrogeological scientists and decision makers in developing countries.

In the calculation of the groundwater footprint only direct water was considered. Virtual water was neglected as available information is limited. In this respect, in the presence of new information, food and non-food goods consumption could be introduced into the water balance to improve the understanding of the water footprint in the context of the aquifers under study.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the

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